A Comparison of the Operations of Single Point and Tight Urban Diamond Interchanges

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ABSTRACT

Single point urban interchanges (SPUIs) and tight urban diamond interchanges (TUDIs) are alternatives typically considered in locations where roadway right-of-way is constrained. The body of research comparing these two interchange types is limited and operational comparisons are varied in their findings. It is believed that the traffic operation performance of these two interchange types does not differ significantly, which makes it challenging for transportation practitioners to select a preferred interchange type for a specific location.

The hypothesis of similar traffic operations performance is tested by comparing the operations of geometrically similar SPUIs and TUDIs for a wide range of volume conditions with microscopic simulation analysis. The analysis was conducted with CORSIM using optimum signal phasing and timing for both interchange types. Three specific test volume cases and five varying volume levels were developed for both interchange types to evaluate the interchanges over a range of capacity conditions. The thirty analysis cases were analyzed using microscopic simulation and the results compared between the interchanges.

The findings show that for the geometric and volume conditions tested the SPUI provides greater traffic operation performance than the TUDI. Over the range of tests the SPUI provided higher average travel speeds, fewer phase failures, a lower percentage of stops and considerably higher capability to serve traffic. The results typically show that the TUDI would reach capacity conditions when the SPUI was operating at average conditions.

INTRODUCTION

Conventional diamond interchanges are the most common type of interchange in the United States. The tight urban diamond interchange (TUDI) is a variation on the conventional diamond interchange with more closely spaced ramp terminals than the conventional diamond interchange. Typically a TUDI will have ramp terminals that are spaced 200 to 400 feet apart. The traffic signals controlling the two ramp intersections on a TUDI are coordinated to move traffic efficiently through the intersections.

The single point urban interchange (SPUI) is a variation on the TUDI where all approaches converge into one intersection above or below the mainline roadway. This intersection is controlled by a single traffic signal. The most important and unconventional operational element of the SPUI is all left-turn movements travel to the inside of one another (termed "inverted" in some documents), which reduces the left-turn conflicts that exists at conventional intersections. The SPUI debuted in the United States in the early 1970s. Since then more than two-hundred SPUIs have been constructed in the U.S. and many more are planned for construction *(1)*. Typical TUDI and SPUI layouts are shown in Figure 1.

These two interchange types are becoming more commonplace because of the need to provide increased roadway capacity in developed areas without requiring additional right-of-way. Transportation practitioners often must select between these interchange alternatives when planning improvement strategies, however, the body of research comparing the operation of these two interchange types is limited and the findings are often conflicting.

Based on the body of past research it is believed that in general the traffic carrying characteristics of SPUIs and TUDIs may not differ significantly. Because of this it is often difficult to identify the best interchange for a specific site. Millions of construction dollars are at stake with each of these decisions as well as many person-hours of delay to the traveling public. Selecting the best interchange alternative for a particular site benefits not only the transportation industry but also, to a greater degree, the public.

To answer this traffic carrying characteristic question, the operational characteristics of a SPUI and a TUDI will be compared for multiple volume conditions with microscopic simulation analysis to determine how the characteristics of the interchanges differ over a wide range of volume levels. This paper reviews past research on the operations of TUDIs and SPUIs. Following this is the analysis methodology used for this research, the research results, and finally, the conclusions.

PREVIOUS RESEARCH ON TUDIs AND SPUIs

Interchange Characteristics

The TUDI is a diamond interchange in which the ramp terminal intersections are more closely spaced than a conventional diamond. Typically the distance between ramp terminals is 200 to 400 feet. The short spacing between ramp terminals results in special operational needs. The traffic signals controlling the two ramp intersections on a TUDI must be coordinated to move traffic efficiently through the intersections and limit internal vehicle queuing. Several special signal timing patterns have been developed for diamond intersections and the signal phasing selected is dependent upon the prevailing traffic flow conditions. Leisch et al. *(2)* compared the SPUI and TUDI in 1989 concluding that the TUDI could accommodate a greater variability in traffic patterns because the TUDI can have a wide range of traffic signal phasing patterns that can be configured to match vehicular demand.

The SPUI is similar to the TUDI with the primary difference being the ramps and cross street all converge on a single intersection above or below the mainline instead of two intersections outside of the mainline. This single intersection is controlled by one traffic signal and usually operates with a three phase timing pattern with overlaps. A three phase timing pattern works at the intersection because the ramp and cross street left-turn movements turn to the inside of one another (also termed as an inverted left-turn). This configuration reduces the number of conflicts as compared to conventional intersections and reduces the number of phases necessary for the intersection from four to three.

Operational Parameters

Operationally, TUDI traffic flow parameters (saturation flow rate, lost time, turning speeds, etc.) are the same as typical at-grade intersections. The key factor in the analysis of TUDIs is the consideration for the interaction of the two intersections. Optimal signal timing should be developed to minimize storage of vehicles between the ramp intersections and provide coordinated movement of traffic along the cross street and from the off-ramps.

Several unique characteristics should be considered in the analysis of the SPUI. The timing of the clearance interval should fully consider the lengthy travel paths through the SPUI signalized intersection. The additional phase clearance times result in increased lost time at the intersection. Poppe et al. *(3)* found the clearance lost time to be closely tied to the length of the clearance interval. The research indicated the clearance lost time was generally 2.5 to 3 seconds shorter than the length of the clearance interval. Poppe also measured the saturation flow rates at SPUIs for this same study. Upchurch and Hook *(4)* later collected data at diamond interchanges to compare to the SPUI data from the Poppe study. Findings indicated no significant differences in saturation flow rates for through movements and cross street left-turn movements, however, they found a difference in saturation flow for off-ramp left-turn movements. SPUIs had significantly higher saturation flow rates for these movements, which was linked to the large left-turn travel path. No significant difference was found in the startup lost time between the SPUI and TUDI.

Messer et al. *(5)* also studied saturation flow rates at SPUIs. The research findings correspond with the Upchurch and Hook findings where the SPUI ramp left-turn movement is significantly higher than the TUDI ramp and typical left-turn movements. Studies have also demonstrated a correlation between the SPUI left-turn movement saturation flow rate and the left-turn path radius through the SPUI signalized intersection. Findings from Bonneson *(6)* indicate the headway reduces as the turn path radius increases.

Interchange Capacity Comparisons

Several comparative studies have been conducted in the last 23 years with a wide range of findings. Leisch et al. *(2)* conducted a comparative study in the late 1980s that utilized TRANSYT-7F to analyze and compare the two interchange types at five actual locations. The general conclusions from the analysis were that the TUDI is more efficient than the SPUI for most traffic conditions and applications are limited for the SPUI. Fowler *(7)* developed twelve traffic volume scenarios and utilized a spreadsheet volume-to-capacity ratio analysis as well as TRANSYT-7F to determine which variations in traffic volume characteristics affected the relative capacities of these two interchanges. Fowler compared volume-to-capacity ratios and intersection delay. He found that the SPUI provided greater capacity than the TUDI for most volume conditions and that the TUDI was more sensitive to variations in traffic volumes. The findings of these two comparative research studies are considerably different and are representative of the wide range of research findings comparing these two interchange types.

Garber and Smith *(8)* conducted detailed capacity evaluations of five existing diamond interchanges (DI) and six existing SPUIs. Their analysis included the use of HCS, Passer III and TRAF-NETSIM. Ten volume scenarios were developed with both low and high volume conditions to test the operations of each interchange. Generally it was shown that the delay at the DI was lower than the SPUI during low volume conditions and under high volume conditions the SPUI provided lower delays. Also, Garber and Smith showed that as the total approach volume levels increased the delays at the DI increased considerably faster than the SPUI. However, one of the conclusions of their study was also a finding that "There is not enough evidence to suggest that there is a significant difference in the average stopped delay per vehicle at SPUIs and DIs."

Summary of Previous Research

The body of research directly comparing TUDIs and SPUIs is limited and the findings from these previous studies are inconclusive. The study methods for these comparisons vary considerably. Typically the measures of effectiveness (MOEs) that were investigated included approach delays, v/c ratios and in a few cases overall system delay. Lacking in previous research on TUDIs and SPUIs are three specific items – multiple volume conditions covering a wide range of operational conditions (LOS B, C, D, E, and F), simulation comparisons where each of the test cases was evaluated with optimized signal timings, and use of a wider range of operational MOEs to better compare the operational characteristics of the interchange system.

The research presented in this paper uses a controlled computer simulation environment to compare a SPUI and TUDI. Multiple volume conditions covering a wide range of operational conditions with optimized signal timings are examined using a wide range of operational and system MOEs. The objective of the research is to better define the operating characteristics of TUDIs and SPUIs.

ANALYSIS METHODOLOGY

Method of Analysis

To provide a more comprehensive comparison of the interchange operations, multiple volume conditions were developed for evaluation. Each interchange had one geometric condition for this study. Three volume patterns were developed, each with five volume intensities. This resulted in fifteen analysis scenarios for both interchanges and each of these scenarios for the SPUI were directly comparable to the TUDI.

Microscopic simulation was selected as the method for evaluating and comparing the two interchanges. Micro-simulation better estimates operational conditions for closely spaced or interacting intersections as compared to macroscopic analysis techniques. A wide range of volume levels was evaluated, including near capacity and overcapacity conditions. Microscopic simulation is better suited to providing reliable MOEs under congested conditions where macroscopic analysis techniques typically break down and provide erroneous results.

A group of system level MOEs was selected for performing the operational comparison. *Volume served* represents the total number of vehicles that passed through the simulation. *Average speed* is the average speed of all vehicles that pass through the simulation. *Phase failures* is the number of times a signal phase ends prior to serving the demand for that phase. *Percent stops* is the percentage of vehicles that stop during the simulation. *Delay time* is the total amount of delay in vehicle-minutes recorded during the simulation period. These MOEs were selected because they focus on the operation of the interchange types at the system level.

Analysis Tools

The analysis was conducted with three traffic engineering computer programs: Synchro 5.0, Passer III-98 and CORSIM. Synchro 5.0 is a comprehensive network capacity analysis and signal timing software developed by Trafficware Corporation *(9)*. For this study, Synchro was used to optimize the SPUI signal timing plans for each SPUI test case. Passer III-98 (Progression Analysis and Signal System Evaluation Routine) is a diamond interchange traffic signal optimization software developed by the Texas Transportation Institute *(10)*. This program was used to develop the signal timing plans for the TUDI analyses. CORSIM, developed by the U.S. Department of Transportation and Federal Highway Administration, is a time-based, stochastic, microscopic simulation model of vehicles in an urban roadway system *(11, 12)*. This program was used to simulate the interchanges and calculate the MOEs for each of the analysis scenarios. CORSIM was selected as the simulation program for this study in lieu of other simulation programs because of its wide acceptance and its capability of compiling and computing vehicle, movement, link and system-wide MOEs.

Base Geometric Conditions

The goal of this research is to compare the operations of SPUIs and TUDIs using comparable geometrics. Only one geometric data set was to be evaluated so it was important to select geometrics that were general and applicable to real world conditions *(13, 14)*. The key geometric assumptions for the interchanges are:

- Two through lanes in each direction for the cross street,
- Dual left-turn lanes on the cross street and from the ramp terminals,
- A right-turn lane on the off-ramps (with their own lanes to turn into on the cross street), and
- A right-turn lane for cross street to on-ramp movements.

This geometric interchange layout is consistent with higher capacity designs of these two interchange types. The TUDI intersections for this test case are located 200 feet apart, center to center. This intersection spacing for the TUDI results in ramp placement that is nearly identical to the SPUI geometric layout. The geometric diagrams can be seen in Figure 1.

Volume Scenarios

A range of volume conditions was developed to test the capacity of the interchanges. Few of the past research studies tested the operations of these two interchanges with a wide variation in volume conditions. Three separate volume distributions were developed and for each of these distributions, five volume levels were defined that ranged from light volume levels to over capacity conditions. The *balanced volume* condition refers to matched volumes on all of the similar approaches. The *heavy ramp* scenario has one of the off-ramp volumes double the other ramp and the *60/40 directional* condition adjusts all of the volumes to mimic a typical peak hour directional split. The base volume sets are shown in Figure 2.

The base volume scenarios were developed to represent an operational LOS B for the intersection when evaluated in CORSIM based on the SPUI test cases. Four additional volume sets were developed to represent LOS C, D, E and F based on the SPUI test cases. The development of the higher volume conditions was an iterative process in which the volumes were increased by a factor and then evaluated in CORSIM to determine the LOS to make certain the LOS threshold was met. For consistency, the midpoint of each LOS band was targeted during the volume development process. The resulting factors for each of the test cases are summarized in Table 1.

It is important to note that the volume development was based on the SPUI and not the TUDI as the development of the SPUI optimal signal timings was less involved. The TUDI requires the use of both Synchro and Passer III to develop the signal phasings and timings. The SPUI signal timings can be developed with just the use of Synchro. Also, the determination of an overall LOS for the TUDI requires aggregation of the two ramp intersections, whereas the SPUI LOS could be determined directly. More detailed information regarding volume development can be found in "An Operational Comparison of Single Point and Tight Urban Diamond Interchanges with CORSIM, Master's Thesis" *(15)*.

Operational Assumptions

Several operational assumptions were made when setting up the test cases. The goal was to provide a direct comparison between the two interchanges by minimizing the number of variables to contend with at the conclusion of the analysis. For instance, the interchanges were analyzed under isolated conditions so the capacity tests would not be affected by adjacent intersections or frontage road systems. These two interchanges can operate very differently when interconnected with closely space intersections and it was not the intent of this study to include these considerations.

Signal timing considerations included selecting a standard cycle length of 90 seconds for both interchanges *(16, 17)*. Even though one might have a higher natural cycle length and operate marginally better it was decided the interchanges would be compared with the same cycle length. A standard three-phase signal timing scheme was selected for the SPUI. Passer III was used to develop the signal phasing and timing plans for the TUDI scenarios. Passer III calculates several MOEs while determining the optimum phasing and timing plans and ranks the options based on these MOEs. During the timing development process lead-lag diamond phasing, as defined by Passer III, consistently was ranked as the top phasing plan for several of the calculated MOEs *(10)*. For this reason lead-lag phasing with Passer III optimized timings was utilized for all of the TUDI analysis test cases.

Traffic signals were coded as pre-timed in CORSIM for the analysis to minimize result variability that can occur when using semi-actuated or fully-actuated signal control. Past experience with and guidelines for using CORSIM in near capacity and over capacity analyses led to this decision *(18, 19)*.

A geometric assumption was made regarding the configuration of the right-turn lanes on the cross street and ramp terminals for both interchanges. Typically these right-turns are separated from the left-turns by a median and they operate on a yield-controlled basis as they enter the cross-street *(16)*. For the CORSIM analysis the right-turns were not separated from the main intersection approach. They were instead coded to make their turns from the same approach as the left-turn with right-turn overlap phasing and right-turn-on-red allowed. This was done to remove the need for coding short links in the interchange area. If the interchange is coded the way it truly looks, it is necessary to create several short links around the main intersections. CORSIM is a link-node based simulation that can and often does provide odd results when short links (100 feet or less) are coded in a network, especially when saturated conditions are simulated *(20)*. The same geometric assumptions were applied to both SPUIs and TUDIs.

ANALYSIS AND RESULTS

The analysis of the fifteen test cases for each interchange type was conducted as previously discussed. For each test case, ten CORSIM simulation runs were done and the results averaged *(15, 18, 21)*. Each of the ten replicate CORSIM runs used a different random number seed. These same random number seeds were used in each of the test cases.

SPUI Analysis

A standard three-phase SPUI signal timing scheme was utilized with optimal timings generated using Synchro. Left-turn speeds were adjusted to account for the large radius left-turn movements and clearance intervals adjusted to allow for vehicle travel through the sizeable intersection. Clearance intervals for the left-turn movements were set at four seconds and five seconds for the yellow and all-red intervals, respectively. The default left-turn speed was set to twenty miles per hour. Signal timings were manually coded for each test case. Each CORSIM simulation was run for a sixty minute duration.

TUDI Analysis

Passer III-98 was used to develop the signal phasing and timing for each of the fifteen test cases for TUDIs. Lead-lag signal phasings were used. The Passer III-98 timings were coded into Synchro for each test case and then transferred to CORSIM. As with the SPUI analysis each simulation was run for a sixty minute duration.

Results

Five selected system MOEs for all thirty test cases were compiled for comparing the interchanges. Table 2 summarizes the results for all of the SPUI and TUDI test cases. The results are also summarized graphically in Figures 3 through 7. In all figures the first three bars represent the SPUI test cases and the final three bars in each group represent the TUDI test cases.

Figure 3 summarizes the total volume served for all of the test cases. The trend that is shown indicates that SPUI serves a higher volume of traffic than the TUDI for the higher traffic demand levels. Note the heavy ramp SPUI and TUDI tests cases at volume level C serve the same volume of traffic whereas the balanced and 60/40 directional test cases are much lower for the TUDI. This finding is congruent with past research that suggested the TUDI provides higher capacity for unbalanced volume conditions than a SPUI *(4)*. However, the results from this research show that the TUDI only matches the SPUI in total volume served at lower capacity ranges.

The average speed results are shown in Figure 4. Similar speeds were recorded for all volume level B scenarios. Volume levels C, D, E and F, however, show the SPUI to provide considerably higher average speeds. Also note that the SPUI average speeds reduce at a more gradual rate than do the TUDI average speeds. The volume level C heavy ramp TUDI test case has higher average speeds that more closely match the SPUI findings. The average speed for the TUDI quickly drops to match the other TUDI scenarios for volume level D.

The phase failure summary in Figure 5 shows the difference in the gradual increase in SPUI phase failures versus the sharp increase that was recorded for the TUDI. Again, note the low phase failure number for the volume level C heavy ramp TUDI test case. The TUDI phase failures for this test case closely matched the SPUI phase failure numbers.

The summary of percent stops is shown in Figure 6. The number of stops for the SPUI was consistently lower than the TUDI. For the higher volume test cases, the SPUI simulation recorded approximately half the number of stops as for the TUDI.

The summary of delay time is presented in Figure 7. The delay time for the volume levels increased more gradually for the SPUIs than for the TUDIs. The heavy ramp TUDI test case for volume level C showed delays similar to the SPUI findings while the balanced and 60/40 directional TUDI scenarios recorded substantially higher delay times. This shows the TUDI interchange is more suited to unbalanced ramp volumes as was noted in past research. However, results from volume levels D, E and F show delay time is three to four times higher for a TUDI than a SPUI under higher volume conditions.

CONCLUSIONS

The goal of the research presented here was to determine if the operations of SPUIs and TUDIs differ significantly. The body of research on this topic provides conflicting and sometimes inconclusive results. To test the operations of the two interchanges, a single geometric test case was developed for each interchange with geometrics that have equivalent characteristics. Three specific volume test cases were developed with five volume levels each. This resulted in the development of thirty CORSIM models each with specifically optimized signal timings.

The analysis conducted shows that for the geometric, volumes and traffic control conditions tested, the SPUI provides better system operational performance than the TUDI. The SPUI had lower delays, higher average travel speeds, fewer phase failures, lower percentage of stops and higher traffic carrying capabilities.

These results support Fowler's *(7)* findings where he stated, "the SPUI provides greater capacity than the TDI" and "the capacity of the TDI is more sensitive to variations in traffic volumes." Garber and

Smith *(8)* showed that as the total approach volume levels increased, the delays at the diamond interchange increased considerably faster than the SPUI. However, they stated there was not enough evidence to suggest that there is a significant difference in the average stopped delay per vehicle at SPUIs and diamond interchanges. The research reported here supports the finding that delays at a diamond interchange increase considerably faster than at a geometrically similar SPUI. Overall, it was shown that a SPUI could serve as much as ninety percent more entering traffic volume than the TUDI for the volume and geometric conditions tested for this research.

It is important to summarize the study methods and assumptions to help the reader determine how this study can be of use to the transportation industry. First, the study was based on one geometric data set in which comparable geometries were defined and assumed to be equal. The validity of this assumption was confirmed in a review of the analysis results – the SPUI and TUDI MOE results were nearly identical for the lowest volume condition tested that was set at LOS B (Figures 3 – 7).

Three separate peak hour volume distributions were evaluated for the study. While the volumes did provide considerable comparative data, it did not provide a comprehensive analysis of all possible volume conditions.

Also, the study was conducted without field data or field calibration. CORSIM calibration was conducted based upon previous research findings, recommendations and simulation experience. Cycle lengths were set at ninety seconds for both interchanges, even though research suggests improved efficiencies with longer cycle lengths for SPUIs. Only one signal phasing pattern was utilized for each interchange and it was assumed that Synchro would provide optimized SPUI signal splits and that Passer III would provide optimized TUDI signal splits. The interchanges were also assumed to be isolated for the analysis, meaning no closely spaced intersections or integrated frontage road systems affected the traffic patterns at the interchanges.

Further study could include additional geometric data sets to determine how geometric variations affect the operational differences of the interchanges. Variation in cycle lengths could be studied, including comparing the interchanges with optimum cycle lengths or testing multiple signal phasing solutions.

Further study could also be conducted to determine what effect the addition of integrated frontage roads would have on the results. Based on past research it is thought that interacting signal and roadway systems would reduce the capacity of the SPUI and that it would be more comparable with the TUDI configuration. Given the traffic handling difference identified between these two interchange types, it is conceivable that the SPUI would still provide superior performance when compared to the TUDI.

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LIST OF TABLES AND FIGURES

TABLE 1 Test case volume factors

Test Case	Level of Service				
	B	C	D	E	F
Balanced	1.00	1.70	2.00	2.10	2.20
Heavy Ramp	1.00	1.40	1.65	1.75	1.85
60/40 Directional	1.00	1.70	2.00	2.20	2.50

TABLE 2 Simulation results (a) Balanced test case (b) Heavy ramp test case (c) 60/40 directional test case

(a)

Balanced Test Case Volume Condition	Interchange	Volume Served	Average Speed (mph)	Phase Failures	Percent Stops	Delay Time (veh-min)
B	SPUI	3,798	23.7	0	64.8	2,289
	TUDI	*3,796*	*22.0*	*0*	*85.0*	*2,446*
C	SPUI	6,454	22.0	10	68.6	4,177
	TUDI	*4,817*	*11.4*	*114*	*133.6*	*23,225*
D	SPUI	7,516	16.6	95	80.5	7,685
	TUDI	*3,885*	*4.5*	*220*	*193.2*	*43,458*
E	SPUI	7,415	11.7	130	130.0	12,108
	TUDI	*3,580*	*3.8*	*231*	*231.3*	*46,917*
F	SPUI	7,355	10.0	140	105.8	14,511
	TUDI	*3,504*	*3.6*	*235*	*213.5*	*47,895*

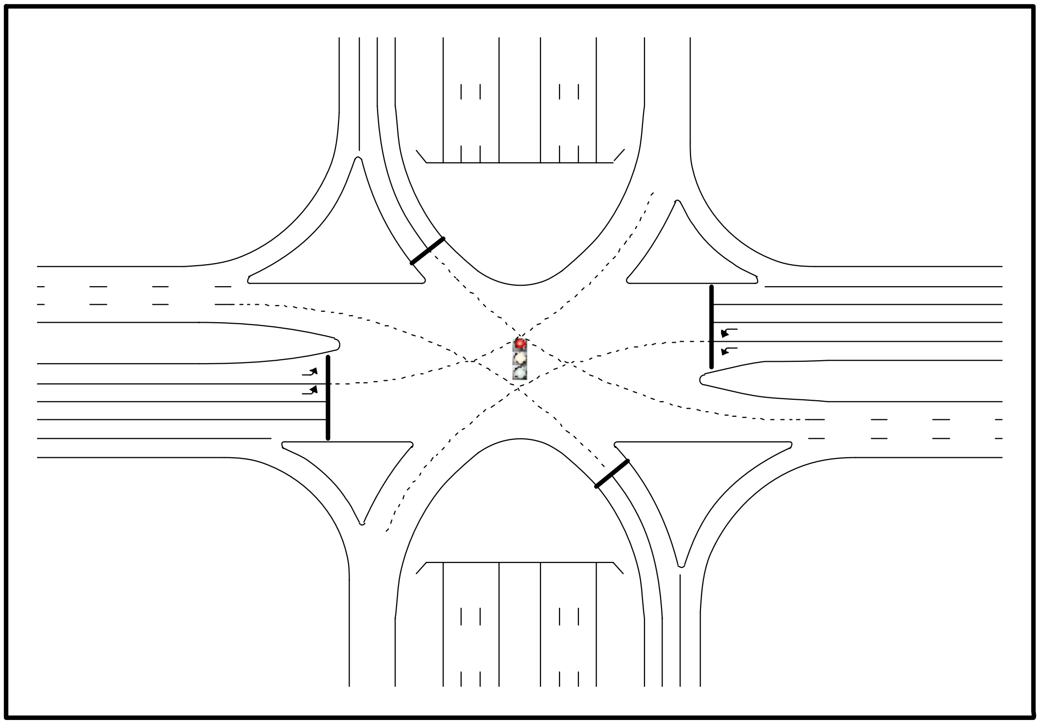
(b)

Heavy Ramp Test Case Volume Condition	Interchange	Volume Served	Average Speed (mph)	Phase Failures	Percent Stops	Delay Time (veh-min)
B	SPUI	4,297	23.3	0	64.9	2,645
	TUDI	*4,298*	*21.4*	*0*	*83.3*	*2,870*
C	SPUI	6,011	21.9	5	69.8	4,055
	TUDI	*5,974*	*19.4*	*8*	*90.5*	*5,393*
D	SPUI	6,951	15.8	60	93.4	7,683
	TUDI	*4,410*	*5.3*	*193*	*168.8*	*39,543*
E	SPUI	6,999	11.5	107	99.4	11,979
	TUDI	*3,954*	*4.2*	*215*	*190.4*	*45,485*
F	SPUI	6,931	10.0	104	100.1	14,106
	TUDI	*4,479*	*5.2*	*203*	*183.1*	*40,594*

(c)

60/40 Directional Test Case Volume Condition	Interchange	Volume Served	Average Speed (mph)	Phase Failures	Percent Stops	Delay Time (veh-min)
B	SPUI	3,800	24.3	0	61.3	2,100
	TUDI	*3,804*	*21.3*	*0*	*79.6*	*2,582*
C	SPUI	6,459	23.0	13	63.8	3,742
	TUDI	*4,339*	*6.2*	*170*	*155.7*	*32,710*
D	SPUI	7,287	15.1	65	80.5	7,767
	TUDI	*3,702*	*4.3*	*223*	*187.2*	*44,792*
E	SPUI	7,471	11.8	90	92.3	11,553
	TUDI	*3,595*	*3.6*	*233*	*210.2*	*48,060*
F	SPUI	7,423	10.2	89	98.3	13,637
	TUDI	*3,495*	*3.2*	*236*	*219.0*	*49,503*

(a)



(b)

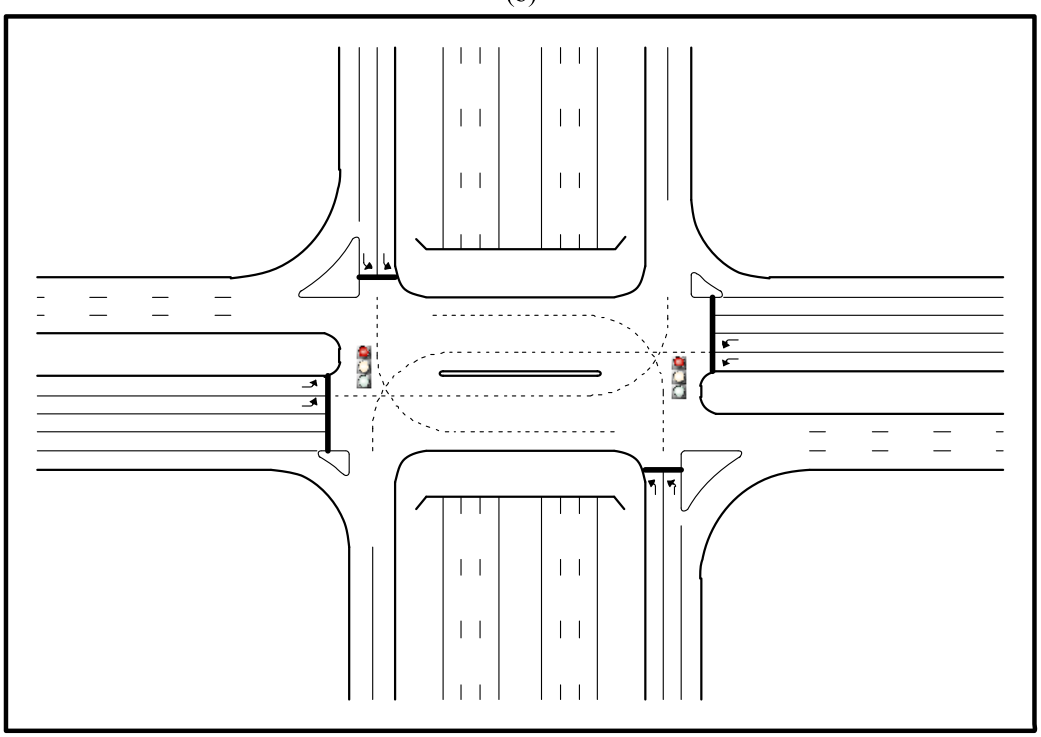


FIGURE 1 Typical interchange geometries. (a) SPUI. (b) TUDI.

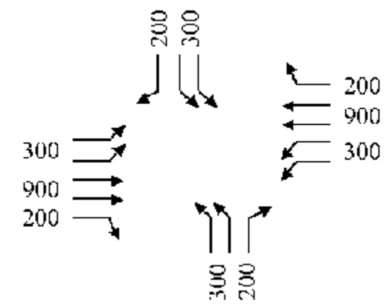
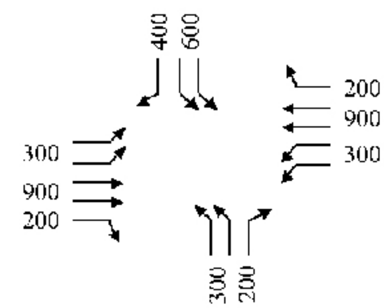
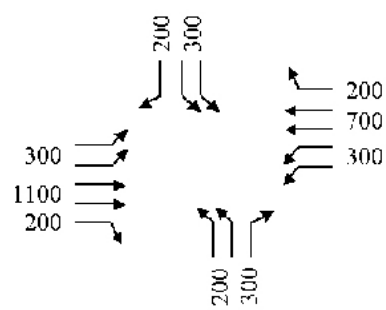
Volume Condition	Design Hour Volumes/Lane Arrangements
Balanced	
Heavy Ramp	
60/40 Directional	

FIGURE 2 Base Volume Test Cases.

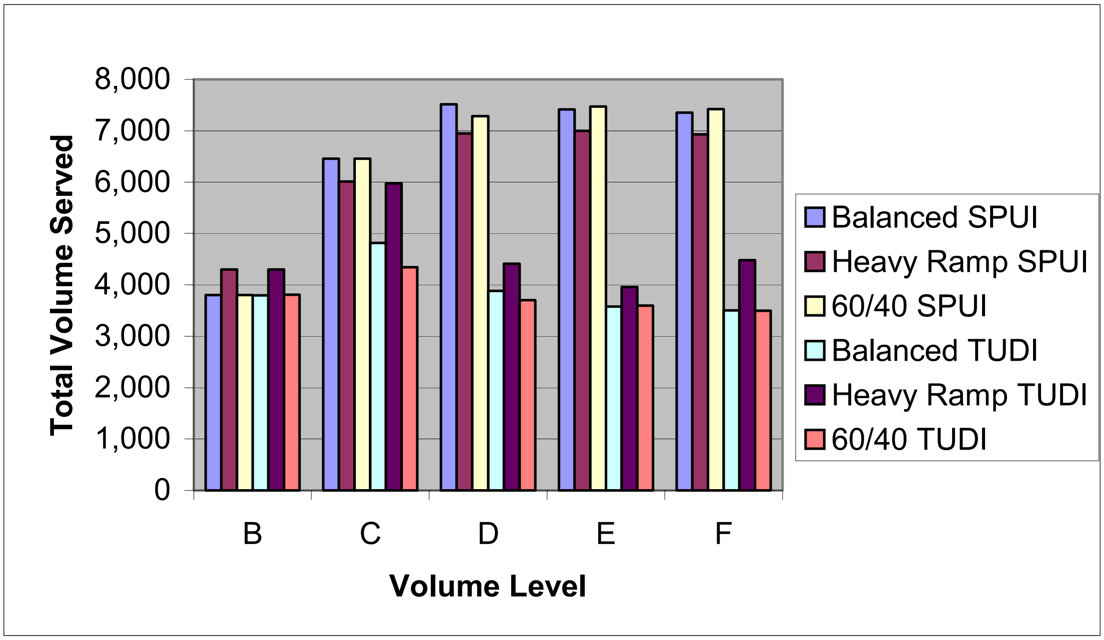


FIGURE 3 Operational performance results – total volume.

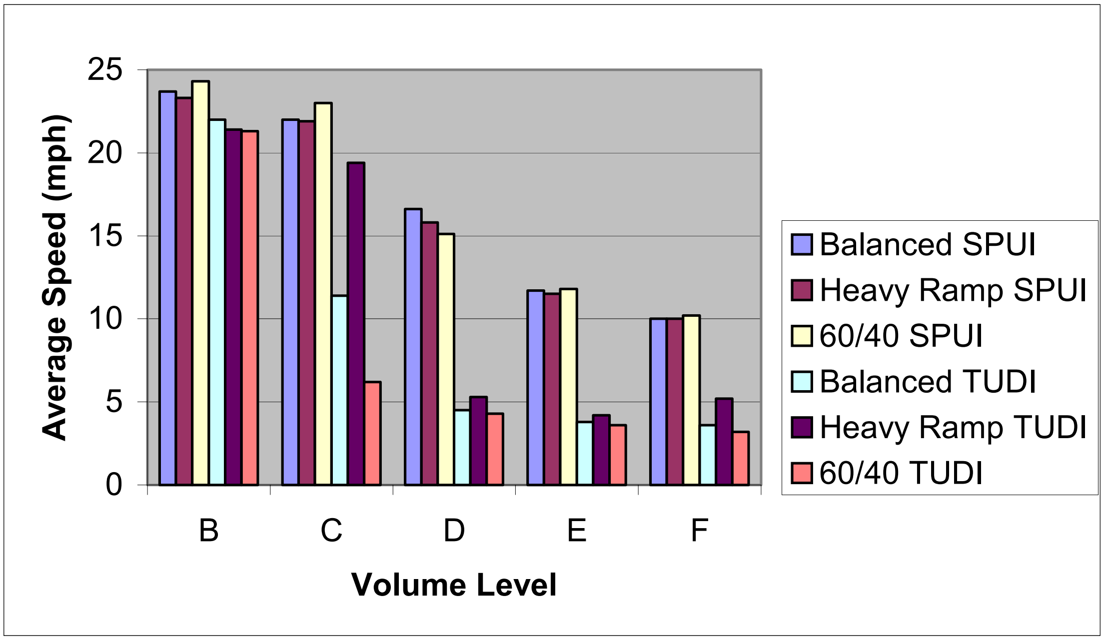


FIGURE 4 Operational performance results – average speed.

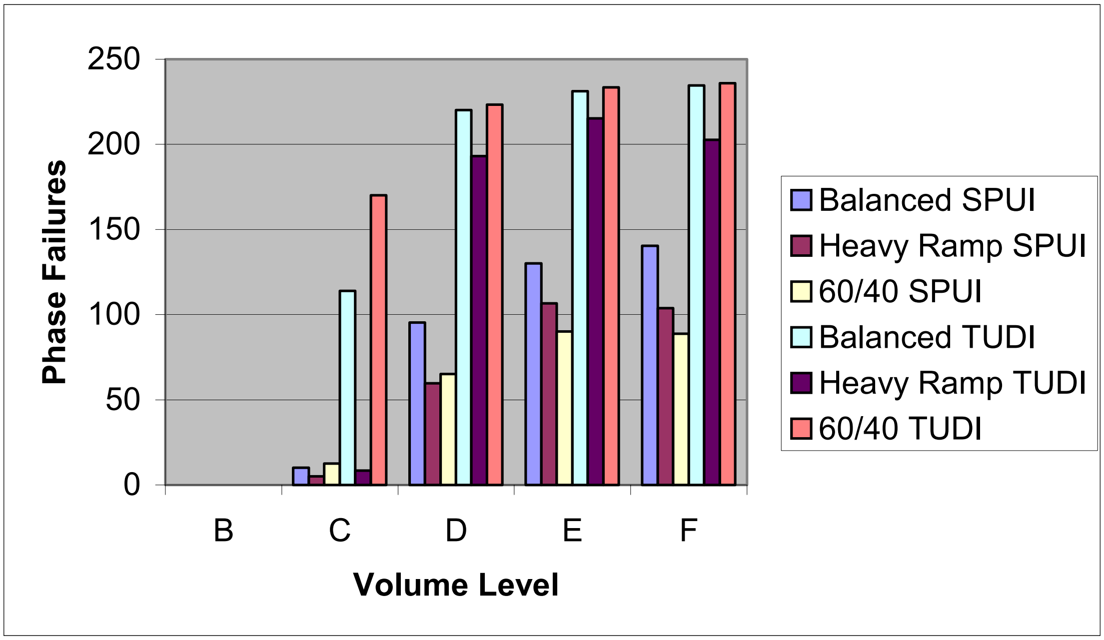


FIGURE 5 Operational performance results – phase failures.

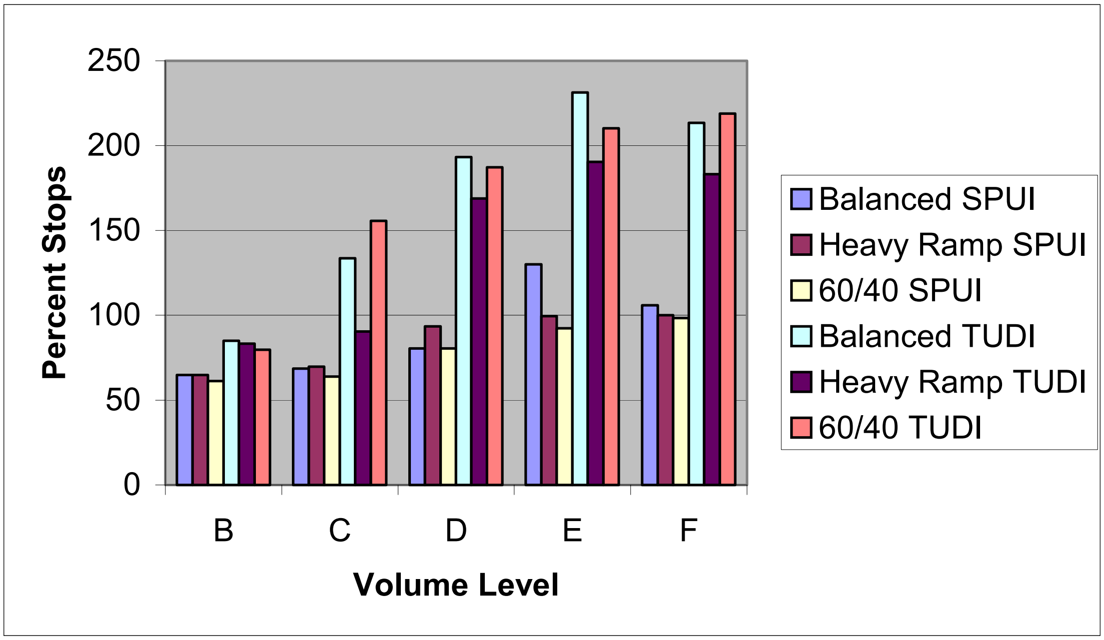


FIGURE 6 Operational performance results – percent stops.

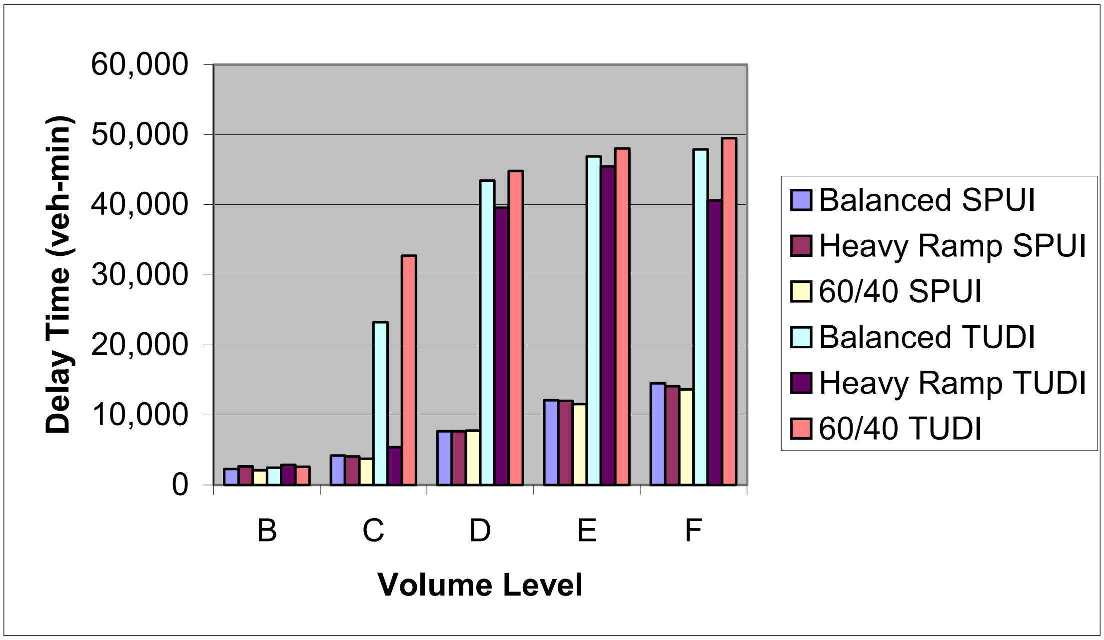


FIGURE 7 Operational performance results – delay time.